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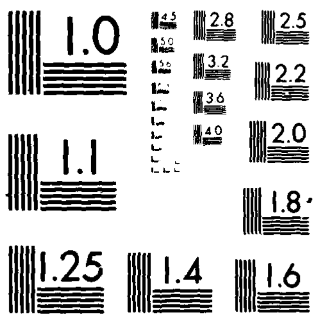

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SIMULATION OF NUCLEAR UNDERWATER SHOCK WAVES USING PLANAR SOURCES: AN INVESTIGATION OF FEASIBILITY

AD A096776

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30 April 1980

Final Report for Period 23 July 1979—30 April 1980

CONTRACT No. DNA 001-79-C-0396

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19 REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: DNA 5340F	2. GOVT ACCESSION NO.: AD-A096 776	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) SIMULATION OF NUCLEAR UNDERWATER SHOCK WAVES USING PLANAR SOURCES: AN INVESTIGATION OF FEASIBILITY.		5. TYPE OF REPORT & PERIOD COVERED: (9) Final Report, for Period 23 Jul 79—30 Apr 80
		6. PERFORMING ORG. REPORT NUMBER: (14) PIFR-1320
7. AUTHOR(s): (10) Jeffrey M. Thomsen, Roland R. Franzen		8. CONTRACT OR GRANT NUMBER(s): (15) DNA 001-79-C-0396
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Physics International Company, 2700 Merced Street, San Leandro, California 94577		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) Subtask Y99QAXSD070-52
11. CONTROLLING OFFICE NAME AND ADDRESS: Director, Defense Nuclear Agency, Washington, D.C. 20305		12. REPORT DATE: (11) 30 Apr[redacted]80
		13. NUMBER OF PAGES: 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 58 (17) D070		15. SECURITY CLASS (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Code B344079464 Y99QAXSD07052 H2590D.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shock Block Program	High Explosive Devices
NWE Simulation	Gun Propellant Devices
Underwater Shock Wave	Long Duration Shock Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Various high explosive and/or propellant sources were assessed for use in the Shock Block nuclear simulation development program. The purpose of this program is to design and engineer a planar source that can develop a fast risetime (~ 0.1 ms), long pulse width (~ 5 ms) pressure pulse at a constant amplitude of ~ 20 MPa (3000 psi) in water. Assessment techniques included: (1) a survey of the properties of fast-burning propellants; (2) one- and two-dimensional finite-difference calculations of candidate

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20. ABSTRACT (Continued)

charge designs in a water environment; and (3) small-scale experiments investigating the feasibility of developing an HE/propellant charge. Recommendations are made concerning the design of future charges to be tested in the continuing program. These designs rely on: (1) decoupling the high explosive source from the water by means of an air gap; (2) forcing the explosive gases to push a steel plate; and (3) sealing the charge edges as means to ensure a more constant pressure source for the simulation technique. The computed results are made credible by their close agreement with data from a previous Shock Block test.

PREFACE

The authors would like to thank Mr. John Gordon of the Underwater Explosions Research Division (UERD) of the David Taylor Naval Ship Research and Development Center, Portsmouth, Virginia, and Messrs. Coye Vincent and Frank Ford of Physics Applications, Inc., Fremont, California, for many useful technical discussions throughout the program. They would also like to thank Mr. Michael Austin, Mr. Stephen F. Ruhl, and Mr. Ted Bakowski of Physics International Company for their help in performing the calculations discussed in this report. Finally, the authors would like to thank Ms. Vera L. Terry for initial typing and Ms. Gloria M. Lawler for editing.

During this program, Commander Thomas J. Deevy, USN, was the DNA Contracting Officer's Representative. The authors thank him for many useful technical discussions and administrative support throughout the program. Dr. Eugene Sevin was the Chief of the DNA Strategic Structures Division, which funded the effort.

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SECTION 1

INTRODUCTION

Physics International Company (PI) participated in the Defense Nuclear Agency's Shock Block Development Program. The objective of the program is to generate in water a planar shock wave that has the characteristics of the nuclear-generated pulse shown in Figure 1.1. Previous tests using a planar high explosive (Primacord*) source in this program are described in References 1 and 2. The purpose of the PI effort was to investigate the use of propellants to improve the performance of underwater shock simulators fielded by the Underwater Explosions Research Division (UERD) of the David W. Taylor Naval Ship Research and Development Center, Portsmouth, Virginia. Limitations on the simulation design include a maximum charge array of 7.3 m x 7.3 m (24 ft x 24 ft) and a high explosive weight limit of 68 kg (150 lb). Results of previous tests have shown that a ~ 0.1 ms pulse risetime can be achieved using the Primacord arrays, but the total measured pulse duration has been less than 1 ms (References 1 and 2).

Because the release of energy is much slower from propellants than from high explosives, it was believed that propellants could be used to obtain a longer duration. At the same time, it was recognized that a fast risetime would be difficult to achieve with propellants alone; therefore, efforts by PI centered on

*Manufactured by the Ensign Bickford Co., Simsbury, Connecticut.

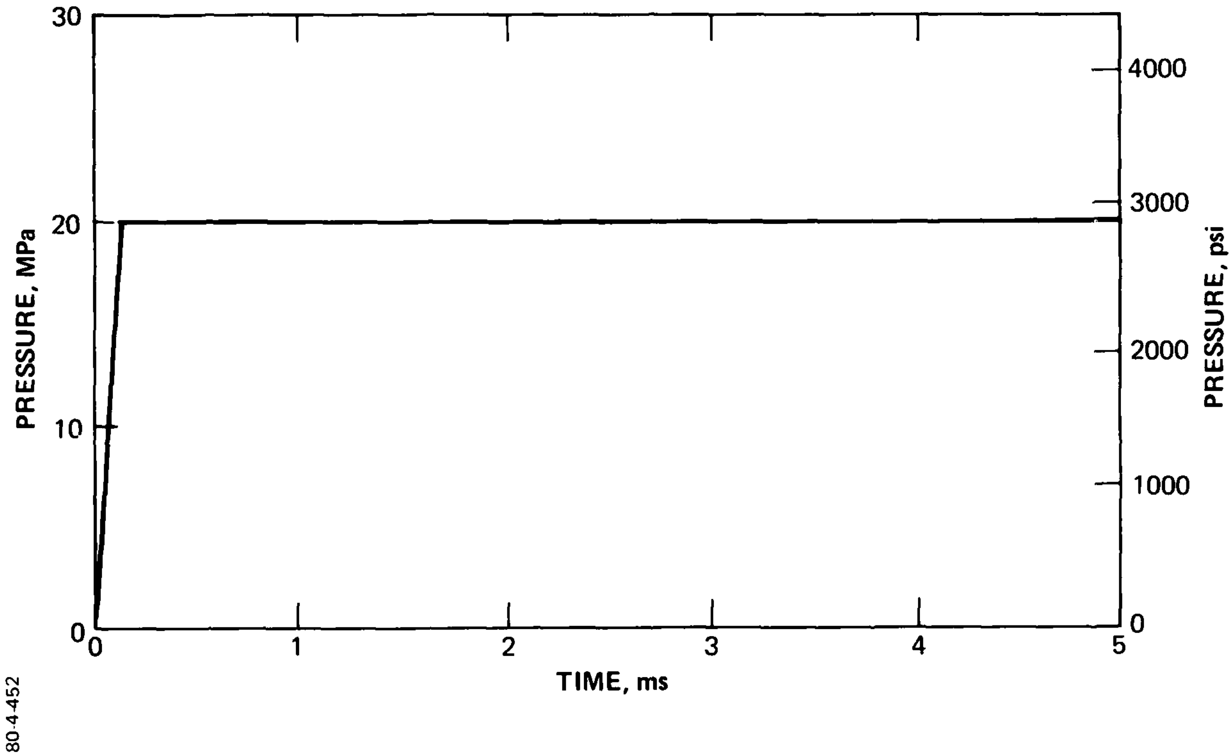

Figure 1.1 Pressure pulse in water typical of a nuclear underwater shock wave, and desired to be simulated with high explosive and/or propellant planar sources in the Shock Block development program.

combining well characterized gun propellants with unconventional, fast-burning propellants, or high explosives, and on improving high explosive (HE) designs. Both theoretical efforts, in the form of one-dimensional (1D) and two-dimensional (2D) calculations, and small-scale experiments were performed. Included was a theoretical analysis of a Shock Block array designed by Physics Applications, Inc. (PAI), and tested by UERD (References 3 and 4). Test results indicated however, that this design (the most successful to date in producing the desired pressure pulse) resulted in a nonplanar pressure wave which had numerous undesirable pressure oscillations superimposed.

This report summarizes the results of the above investigations. Recommendations are made in the form of general designs for Shock Block arrays which, if engineered and tested, might considerably improve planar charge performance in the future.

SECTION 2

PROPELLANT SURVEY AND INITIAL THEORETICAL INVESTIGATION

Initial efforts concentrated on surveying gun propellants to see whether any of them could produce the desired 0.1 ms risetime at the required low loading densities.* The maximum pressure desired, 20.4 MPa (3000 psi), dictated that the total propellant loading density be on the order of 0.1 g/cm^3 or less. Gun propellants were closely examined because they typically have faster and more controllable burn rates, and because several have been well-characterized (Reference 5).

Table 2.1 summarizes the important characteristics of four of the fastest burning gun propellants. The propellant burn rate, R (mm/s), is typically of the following form:

$$R = a + b\ P^n \qquad (2.1)$$

where P is pressure (MPa). The burn rate is generally independent of the geometry of the propellant grain. The energy release, and hence the risetime, is, however, dependent on both R and the geometry. An estimate of the minimum (closed-volume) risetime attainable from 0 to 20.4 MPa (0-3000 psi) can be obtained by

*The loading density is defined as the propellant mass divided by the initial volume of the test assembly.

Table 2.1 Summary of the important characteristics of fast-burning gun propellants.

Propellant	Use	Geometry and Dimensions	Burn Rate, R Coefficients*			Approximate Risetime to 20.4 MPa Maximum Pressure (ms)
			a	b	n	
M18	U.S. Army small arms ammunition	ball, average diam. = 0.71 mm	0	3.075	0.8053	17.6
IMR	U.S. Army rifle ammunition	hollow cylinders, i.d. = 0.18 mm o.d. = 0.81 mm ℓ = 1.43 mm	0	2.40	0.70	25.7
SPDN	U.S. Navy gun propellant	hollow cylinders, i.d. = 0.058 mm o.d. = 0.527 mm ℓ = 1.74 mm	0	2.50	0.7	18.3
M8	U.S. Army mortar ammunition	flake, thickness = 0.102 mm	0.38	2.31	0.878	2.85

*R (mm/s) = a(mm/s) + b(mm/s/MPa^n) . [P(MPa)]^n

calculating the burn rate for a pressure of 10.2 MPa (1500 psi) and dividing it into the propellant web size. (The propellant web size is the shortest distance normal to a burning surface that the grain burns before it loses its structural integrity.) As can be seen from Table 2.1, M8 U.S. Army mortar propellant gives the shortest risetime in a closed volume.

The underwater system is not, however, a closed volume, since the propellant can expand into the water. A calculation was performed using the PISCES 2DELK finite difference computer code (Reference 6) in 1D planar symmetry. A 3-cm-thick slab representing a dual propellant source, M8 mortar propellant at a loading density of 0.0256 g/cm^3 and SPDN U.S. Navy gun propellant at a loading density of 0.028 g/cm^3 was used. The propellant mixture was burned using the propellant burn routine previously programmed for PISCES 2DELK (Reference 7). This source was allowed to expand into 10 m of water. The pressure history developed in the source cavity is compared with the desired wave shape in Figure 2.1. A risetime of 2.5 to 3.0 ms to a pressure of 20 MPa is calculated. This compares well with the closed volume estimate given in Table 2.1 indicating that very little expansion of the source region occurs during the risetime interval.

Based on the above 1D calculation and analysis, pure conventional gun propellant systems were not considered to be viable candidates for improving the Shock Block simulation technique because the desired fast risetime could not be produced.

A new, faster burning propellant, representative of a new family of R&D propellants was seriously considered. This propellant was developed for the U.S. Navy as an igniter material for

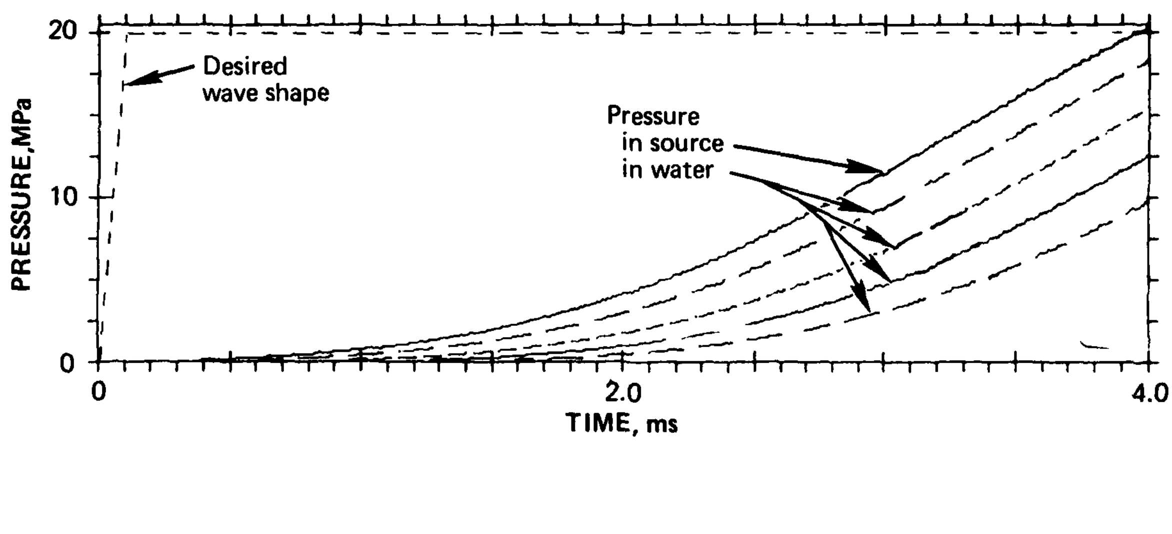

Figure 2.1 Pressure histories in a 3-cm-thick slab propellant source and in water from 1D calculation using M8 fast-burning propellant (loading density of 0.00256 g/cm^3) and SPDN slower-burning propellant (loading density of 0.028 g/cm^3).

Navy guns. Table 2.2 compares the propellant burn properties of the R&D fast-burning propellant No. 134520 with those of SPDN. Of particular interest was the burn rate coefficient, B, and pressure exponent, n. A 1D calculation similar to the one previously discussed was performed using the R&D propellant at a loading density of 0.018 g/cm^3. An acceptable risetime was calculated, as is shown in Figure 2.2. The pressure decay after the peak (20 MPa) is expected because all of the propellant is burned at the time the peak pressure is reached. Addition of a small amount of SPDN to the source region could hold the pressure more constant at later times.

One reason this R&D propellant was a serious candidate as an energy source was that it was designed to be an igniter material for slower burning propellants. High explosives, detonating near propellants, tend to fracture the propellant grains, causing them to burn at a much faster rate than desired, or to not burn at all. The use of the igniter propellant would solve the risetime problem as well as the problem of how to ignite the slower burning propellant. However, because of the excessive cost of this propellant, the Shock Block simulator designs using this propellant were not pursued further in this investigation.

Table 2.2 Comparison of propellant burn properties of R&D propellant 134520* with SPDN conventional gun propellant.

Constant	134520**	SPDN
Impetus, J/g, (ft-lb/lb)	1087.8 (364,128)	935 (312,980)
Grain density, g/cm^3	1.4-1.6	1.58
Covolume, η, cm^3/g	1.445	0.933
Mole weight of gases, μ, g/mole	15.0	23.1
Specific heat ratio	1.297	1.251
Burn rate coefficient, B, $mm/(s\text{-}MPa^n)$	344.26	2.50
Burn rate pressure exponent, n	1.66	0.70

* Manufactured by Teledyne-McCormick-Selph, Hollister, California

**These properties are valid for low loading densities on the order of 0.05 g/cm^3

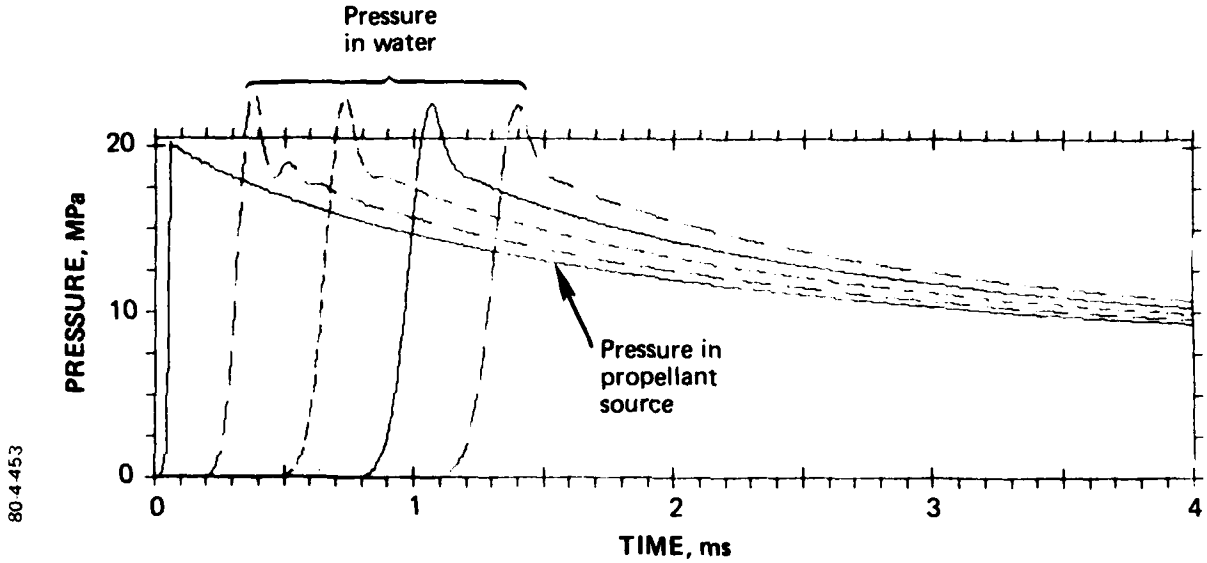

Figure 2.2 Pressure in propellant source region and in water resulting from the burning of R & D propellant No. 134520 at a loading density of 0.018 g/cm^3 in slab symmetry [20 mesh (0.84 mm) grain size].

SECTION 3

SUMMARY OF SMALL-SCALE TESTS PERFORMED TO INVESTIGATE DUAL HIGH EXPLOSIVE-PROPELLANT INITIATION SYSTEMS

Since it appeared that dual propellant systems were either technically unfeasible (because of the long risetime) or not cost effective, HE-propellant systems were investigated. The HE could be used to obtain the desired pressure level quickly, thereby satisfying risetime requirements, and a propellant, or combination of propellants, could be used to maintain the desired pressure level for several milliseconds.

That an HE-propellant system could theoretically deliver the desired wave shape was shown with a 1D calculation. The 3-cm-thick slab source region contained PETN explosive and a combination of propellants--Bullseye (fast burning pistol powder at a loading density of 0.056 g/cm^3) and SPDN (at a loading density of 0.028 g/cm^3). The PETN was assumed to be completely burned, and the detonation gases were spread out uniformly over the source region at an initial pressure of 20 MPa (2940 psi). The calculational geometry is shown in Figure 3.1. Pressure histories were obtained in the water 1.4 m (4.5 ft) from the charge and within the source cavity. These computed pressure histories are shown in Figure 3.2; both the pulse risetime and the pulse width meet the desired specifications.

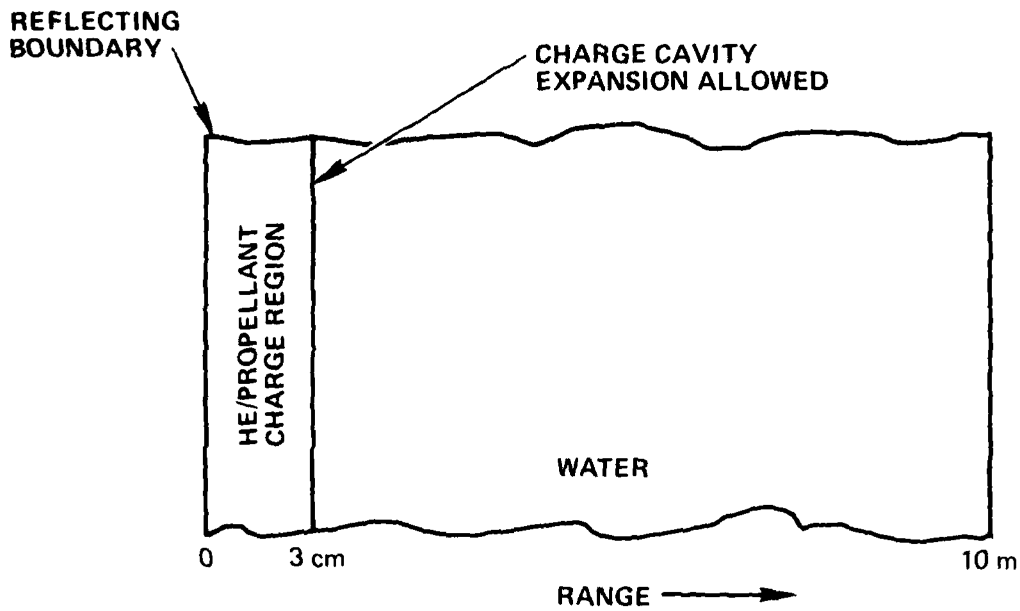

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Figure 3.1 Geometry of PISCES computer code calculation of HE-propellant underwater shock (1D planar symmetry).

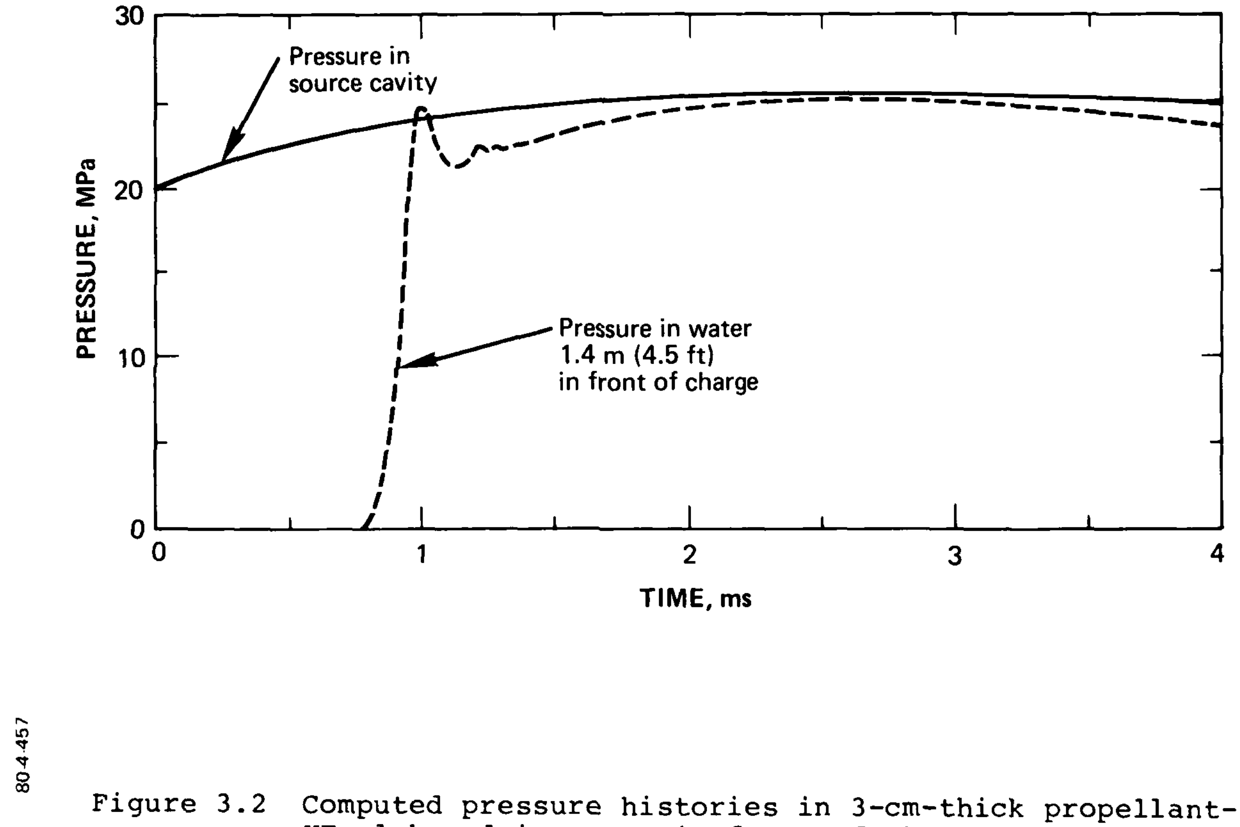

Figure 3.2 Computed pressure histories in 3-cm-thick propellant-HE slab and in water in front of the slab.

It must be noted that these 1D calculations incorporate some assumptions, which are enumerated and discussed below:

1. The shock effects of the HE detonation are ignored. The rate of energy release of a propellant, equivalent to its mass burn rate, is directly proportional to its surface area. If high explosives are detonated in close proximity, shock waves are likely to fracture the propellant, increasing the total surface significantly. This in turn would lead to unpredictable burn rates, a result that would manifest itself in pressure-time curves more characteristic of an HE detonation. Thus the propellants must be protected from shock effects for the 1D calculation to be valid. Also, HE shock effects might produce a sharp initial shock into the water. This might cause the source cavity to expand faster than desired, leading to faster attenuation of the pressure in the source region.

2. Two- and three-dimensional effects are neglected. The actual slab charge would not be infinite in extent; a maximum size is about 7.3 m by 7.3 m (24 ft by 24 ft). The 1D calculations neglect charge edge effects and the effects of the finite detonation velocity of the explosive.

Because of the encouraging theoretical results, small-scale, closed-volume tests were conducted to investigate whether a HE/propellant charge could be properly initiated. These experiments were only a first step in developing a full Shock Block design that could be tested by UERD, but a necessary first step. If technical feasibility were not demonstrated, any further development efforts would be precluded.

It was judged that a dual initiation system had the greatest chance of succeeding. First, the propellant would be ignited; after the propellant grains were burning and the pressure began to increase, the HE would be detonated, instantaneously raising the pressure to approximately 20 MPa. The dual initiation tests were performed in a test assembly shown in Figure 3.3. HE and

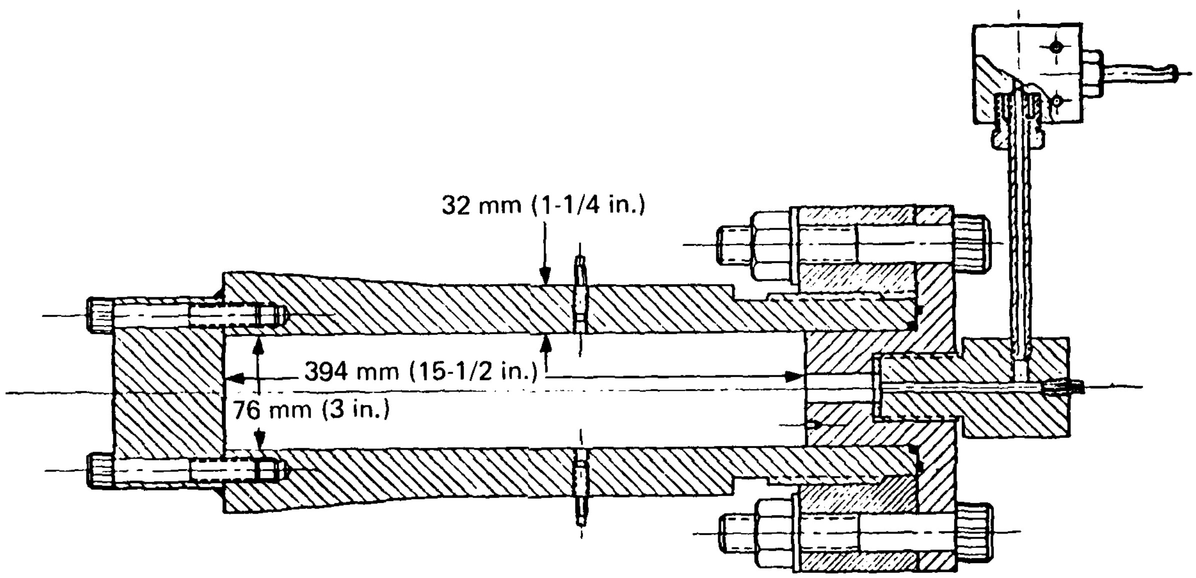

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Figure 3.3 Test assembly for closed volume propellant and HE-propellant initiation tests.

propellant were inserted into the chamber as shown in Figure 3.4. The HE charge consisted of 1.13 m (3.7 ft) of 0.106 gm/cm (50 grain/ft) Primacord cut into four equal sections and taped together. An RP-2 detonator was affixed to one end of the strands, and the entire assembly was wrapped with two layers of aluminum foil. Each of the two propellant assemblies consisted of 5.5 g of SPDN and a S26Cl squib*. The volume of the test chamber was 1795 cm^3, so the propellant loading density was 0.006 g/cm^3. The expected maximum pressure in the tests was 20.4 MPa (3000 psi). This allowed the test chamber (Figure 3.3) to be reused. Pressure within the chamber was monitored using a PCB Model 102A pressure transducer.

Two tests of the above type were performed, one in which the HE was detonated 0.2 ms after propellant ignition, the other, 0.6 ms after ignition. In both tests only the pressure resulting from the HE detonation was recorded, although pressure was monitored for 20 ms in the first test, and 50 ms in the second. It was evident from these tests that the propellant was not burning properly. The time for the propellant to begin to burn over all the surfaces of the grains after initiation was much longer than expected. The propellant grains may have been seriously fractured by the HE detonation or the propellant simply would not burn as anticipated at this low loading density.

To see whether the propellant was burning properly, an additional series of tests was performed using only propellant. The results of these tests, labeled 2-1 to 2-6, are summarized in Table 3.1. Also summarized there are the results of the first two

*Manufactured by Hercules, Inc.

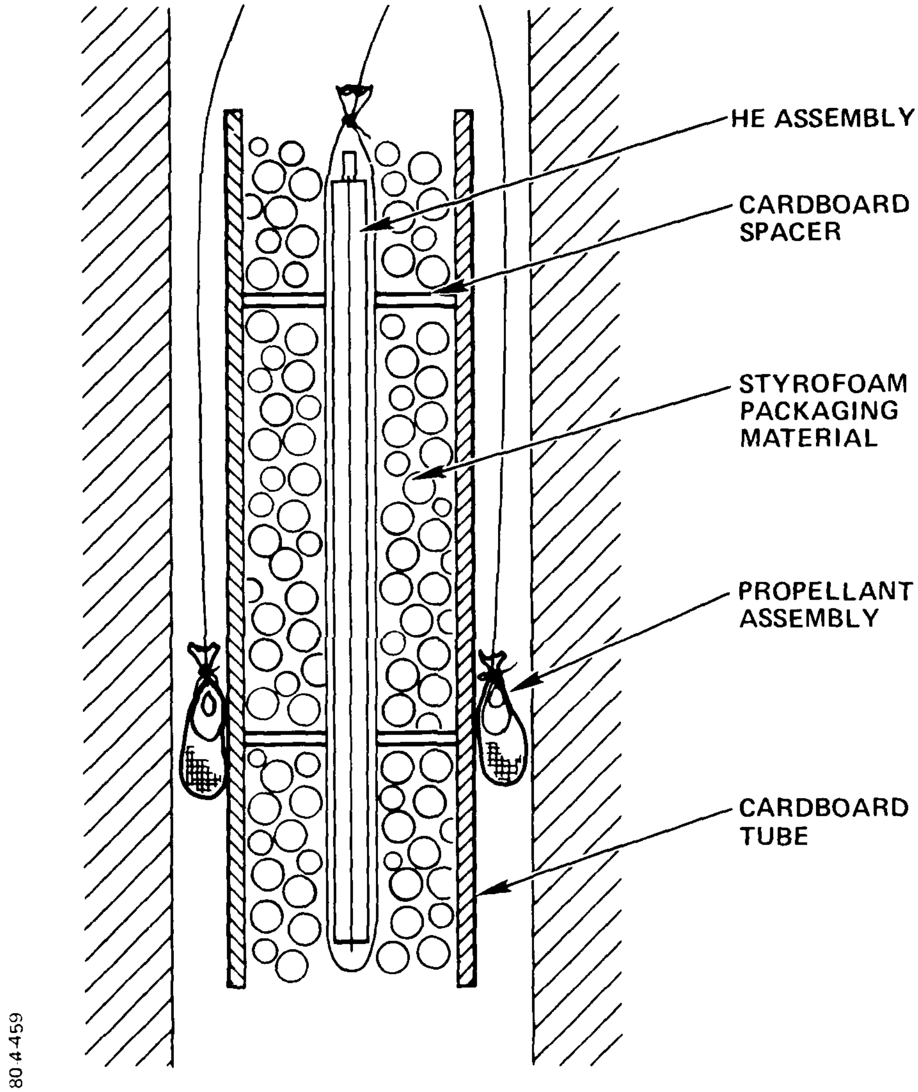

Figure 3.4 HE-propellant charge within closed volume test assembly.

Table 3.1 Summary of HE/propellant initiation timing tests.

Test Number	Charge Description	P_{max} [MPa (psi)]	T* [ms]	Remarks
1	1.13 m Primacord with RP-2 detonator, and propellant charge primer with 11 g SPDN	20.4 (3000)	> 20	HE firing pulse 200 μs after propellant
2	1.13 m Primacord with RP-2 detonator, and propellant charge primer with 11 g	20.4 (3000)	> 50	HE firing pulse 600 μs after propellant
2-1	Propellant charge only, as in 1 and 2	--	>100	
2-2	Propellant charge only, 14.7 g SPDN, initiated by 25.4 cm Pyrofuze**	6.1 (900)	350	
2-3	Propellant charge only, 14.3 g SPDN, initiated by 6.35 cm Pyrofuze	--	240	Incompletely burned
2-4	Propellant charge only, 14.0 g SPDN, initiated by 25.4 cm Pyrofuze	6.1 (900)	1000	
2-5	Propellant charge only, 14.0 g SPDN, initiated by 25.4 cm Pyrofuze	6.1 (900)	500	
2-6	Propellant charge only, 14.0 g SPDN, initiated by 25.4 cm Pyrofuze	6.1 (900)	750	

*Time from initiation to P_{max}

**Manufactured by Pyrofuze Corporation, Mt. Ve[illegible]n, N.Y.

tests. Although the SPDN loading was slightly higher in the second series of tests (0.0077-0.008 g/cm^3), the expected maximum pressure, 6.1 MPa (900 psi) was lower than in the first two tests because no HE was used. In four of these tests, the expected pressure was obtained. A typical waveform is shown in Figure 3.5. Although the maximum pressure and the waveshape were found to be highly repeatable in these tests, the time from initiation to maximum pressure varied greatly.

The above tests showed why the results of the first two tests were not positive: the propellant was not burning completely when the HE was detonated. Furthermore, the time variation from initiation to the beginning of pressurization of the chamber (340-860 ms) was much longer than the propellant pressure risetime (100 ms to one-half maximum pressure). This variation ruled out dual initiation systems because in all probability the HE would not detonate at precisely the proper time. Use of a pressure switch could correct this problem, at least for the small-scale tests, but still precluded the use of such a system in a large-scale Shock Block test where multiple HE/propellant sources would have to be used.

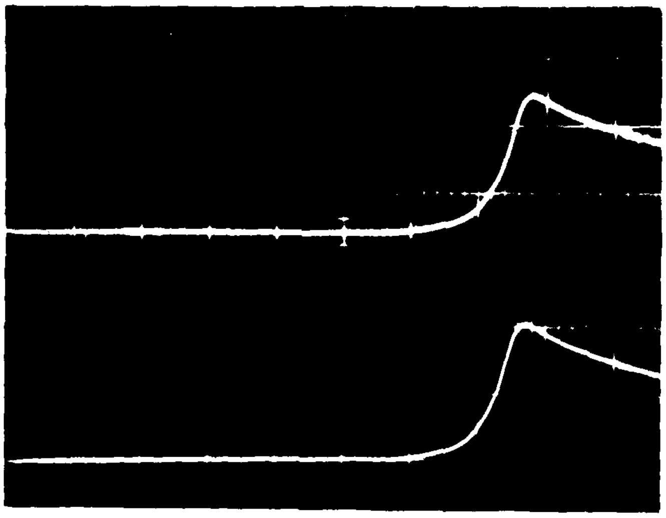

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Figure 3.5 Pressure vs. time for pure propellant closed volume test 2-6 (100 ms/cm, 3 MPa/cm, grid spacing is 1 cm x 1 cm).

SECTION 4

EVALUATION OF A CHARGE DESIGN USING A SLOW-BURNING PROPELLANT INITIALLY CONFINED IN ALUMINUM TUBES

Concurrent with the work performed under this contract, a Shock Block charge was designed by Physics Applications, Inc. (Reference 3) and subsequently tested by UERD (Reference 4). The charges consisted of an array of 19 mm (3/4 in.) diameter aluminum tubes filled with a powdered propellant. Up to 21 of these tubes, 3.3 m (10 ft) long each, were emplaced in a planar array using a 6.1 m x 6.1 m (20 ft x 20 ft) steel backing structure. One experiment, consisting of five 1.8 m (6 ft) tubes, was emplaced with no steel backing structure. A Primacord initiator was used. Pressure was measured in the water 1.07 m (3.5 ft) from the center of the array.

Results of the above series of tests are discussed in References 3 and 4. They can be summarized as follows: an acceptable risetime was achieved, and a pressure pulse of the order of 3-5 MPa (440-735 psi) was maintained for 3.5 ms. A typical pressure history is shown in Figure 4.1; numerous sharp oscillations are superimposed on the underlying 3-5 MPa pressure pulse. Further analysis of the data by UERD indicated that the pressure wave was not planar.

An effort was made to evaluate the PAI design, in part, by performing a two-dimensional calculation. The propellant characteristics were obtained from PAI personnel. The propellant, when confined in the aluminum tube, has a burn velocity along the tube of 0.3 m/ms (1.0 ft/ms). At an initial density of 1.3 g/cm^3, the

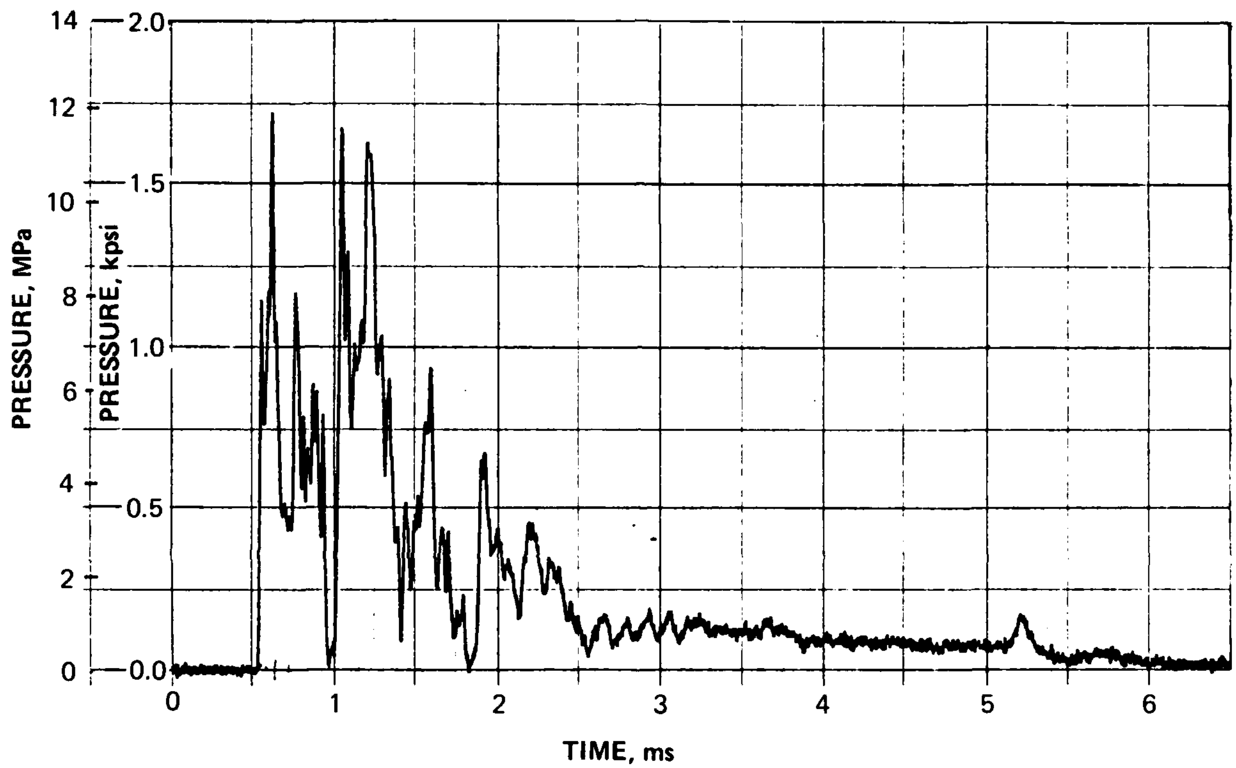

Figure 4.1 Pressure vs. time in front of charge sheet from UERD Shot 9036, using PAI propellant design (pressure gage P2, data used with permission of Mr. J.D. Gordon, UERD).

propellant pressure developed within the 17.3 mm (0.68 in.) i.d. aluminum tube is 117 MPa (17,000 psi). The energy released is 3223 J/g (770 cal/g).

We attempted to determine whether this Shock Block design could be improved. Even with no steel backing plate, the problem of calculating the pressure in the water from an array of tubular gas sources is three-dimensional. It is possible to calculate the pressure history from a single tube using axial symmetry, however. Since the burn velocity of the propellant in the tube (0.3 m/ms) is a factor of 5 less than the speed of sound in water, the pressure field in the water surrounding the tube was suspected to be highly two-dimensional. A calculation of the burn of a single tube in a water environment was warranted for the above reason, and was performed.

Figure 4.2 shows the zoning for the 2-D calculation. The propellant tube was assumed to have a radius of 0.864 cm (0.68 in inside diameter). The aluminum tube was neglected during the propellant expansion phase following propellant burn. The tube was not allowed to collapse if shocked by the water before the propellant inside it had burned, however. The propellant was burned in Lagrangian coordinates at a constant velocity of 0.305 m/ms. As the burned propellant expanded, it was allowed to interact with the Eulerian water region using the coupled Eulerian-Lagrangian logic of PISCES 2DELK (Reference 6).

The water had an initial density of 1.0 g/cm^3 and was described using a Hugoniot relationship of the form

$$P = A_1\mu + A_2\mu^2 \qquad (4.1)$$

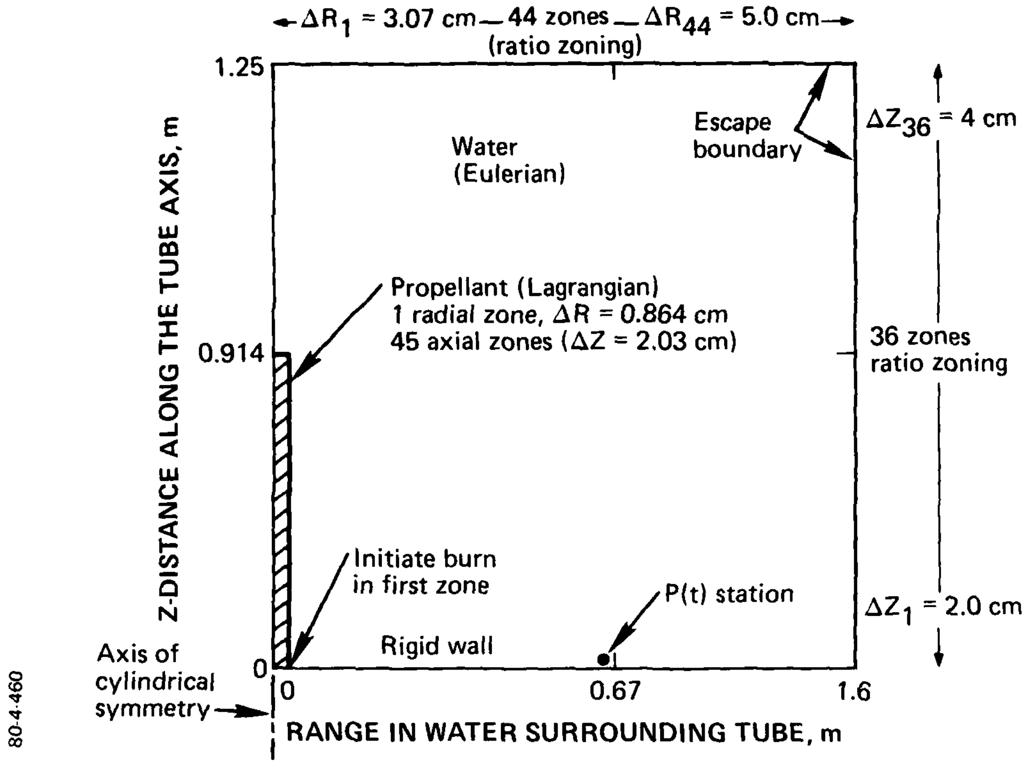

Figure 4.2 Zoning and material boundaries for PISCES 2DELK calculation of a single 1.83 m (6 ft) PAI propellant tube burning in a water environment (figure not to scale).

where P is the pressure and μ is the compressibility ($\mu \equiv \rho/\rho_o - 1$ where ρ is the current density and $\rho_o = 1\ g/cm^3$). The constants A_1 ($A_1 = 2.188$ GPa, $A_2 = 6.028$ GPa) were set so that the initial sound speed in water would be 1.48 m/ms. The propellant was given the properties obtained from PAI, as discussed previously.

The 2D calculation was run to a total time of 1.5 ms. This was only half the time required to burn the entire tube, but in order to obtain sufficient resolution in the water during the first half of the burn, it was not possible to calculate the entire burn without an extensive rezone. Sufficient information was obtained from the first (1.5 ms) run, so the second run was not made.

Figure 4.3 presents pressure contours in the water for pressures of 0.2 MPa (29.4 psi), 1.0 MPa (147 psi), 3 MPa (440 psi), and 5 MPa (735 psi) at a time of 0.5 ms. At that time, 0.16 m (0.5 ft) of the propellant tube had burned, the position of the burn front is indicated on the figure. Because of the higher sound speed in the water, all of these low pressure contours extend almost spherically from the origin. It is easy to see that, even at these low pressures, the pressure wave in the water is not planar.

Of greater interest are higher pressures, at least on the order of 10 MPa (1470 psi). Figure 4.4 gives pressure contours for 3, 5, and 10 MPa at a time of 1.0 ms. The 10 MPa contour encloses the burn front and extends behind it, but not all the way to the original detonator position. Further analysis showed that this closed pressure contour moves with the burn front at approximately the burn velocity.

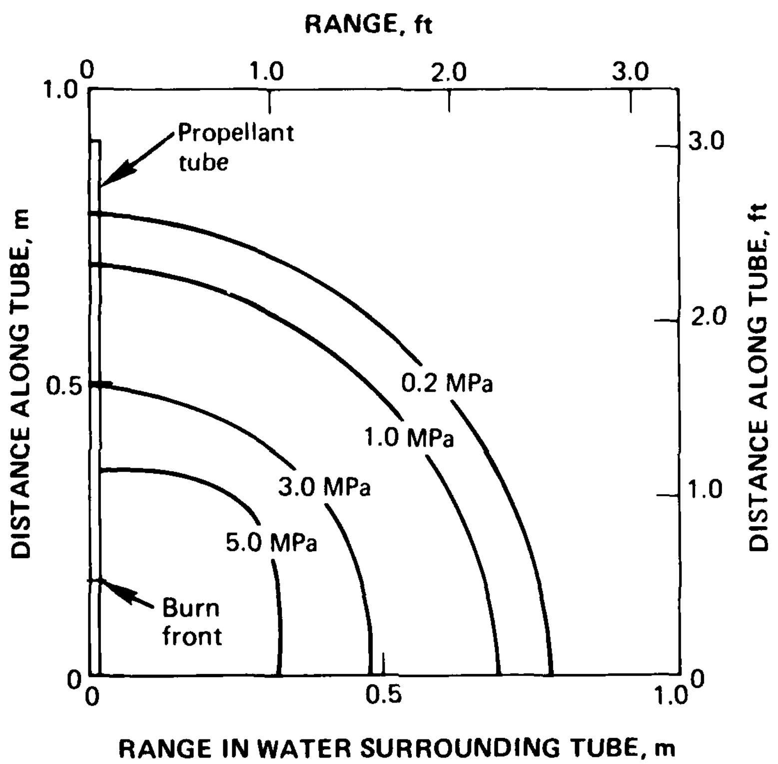

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Figure 4.3 Pressure contour plot from 2D calculation of a PAI propellant tube burning in a water environment at a time of 0.5 ms.

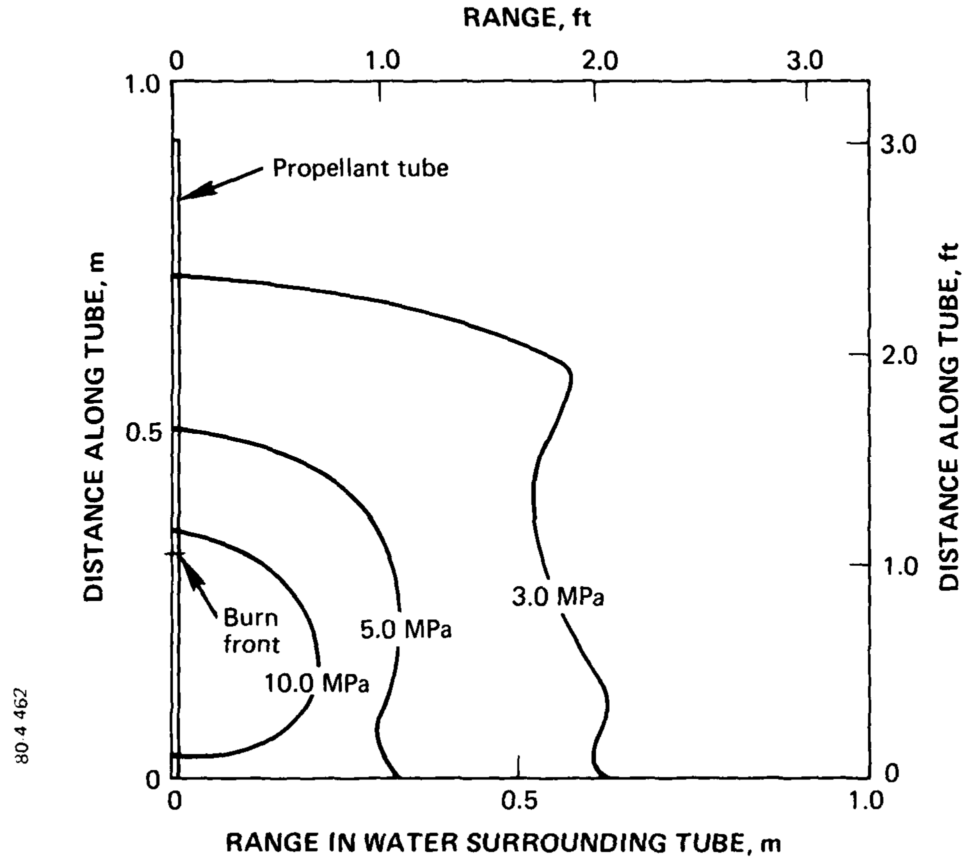

Figure 4.4 Pressure contour plot from 2D calculation of a PAI propellant tube burning in a water environment at a time of 1.0 ms.

The pressure history in the water at the center of the 1.8 m (6 ft) propellant tube, at a range of 0.67 m (2.2 ft) is shown in Figure 4.5. A fast risetime (< 0.1 ms) is obtained, and the pressure is maintained at a level of between 2 and 3 MPa to past a time of 1.5 ms. The superimposed pressure spikes are due to the burn of individual cells of the propellant tube, and changing the zoning of the tube would probably change their amplitude and frequency. In general, the waveform obtained is very similar to that obtained in the experiment. Uneven tube rupturing could be responsible for the pressure spikes in the data, but this may or may not correspond to a discretely zoned, finite-difference approximation to the propellant burn used here.

In conclusion, the 2D calculation gives a pressure pulse in the water that closely resembles the experimental data, even neglecting multiple tube effects. The pressure pulse calculated is not planar, however. In fact, the higher the pressure level, the less planar the wave appears. At pressures of highest interest, those above 10 MPa (~ 1500 psi), the wave is roughly spherical, and closely follows the burn front in the propellant.

An improvement could be made in this Shock Block design by igniting the propellant at more locations along the tube. For example, if the detonator spacing along the tube were 0.3 m (1 ft), the time to burn the propellant between detonators would be 0.5 ms; for a spacing of 0.15 m (6 in.), the time would be 0.25 ms. The latter time is on the order of the Primacord burn time across a 3.0 m (10 ft) array (0.22 ms), assuming detonation at the center of the array, so the pressure wave produced by such a multipoint-detonated array is probably about as planar as one could hope for.

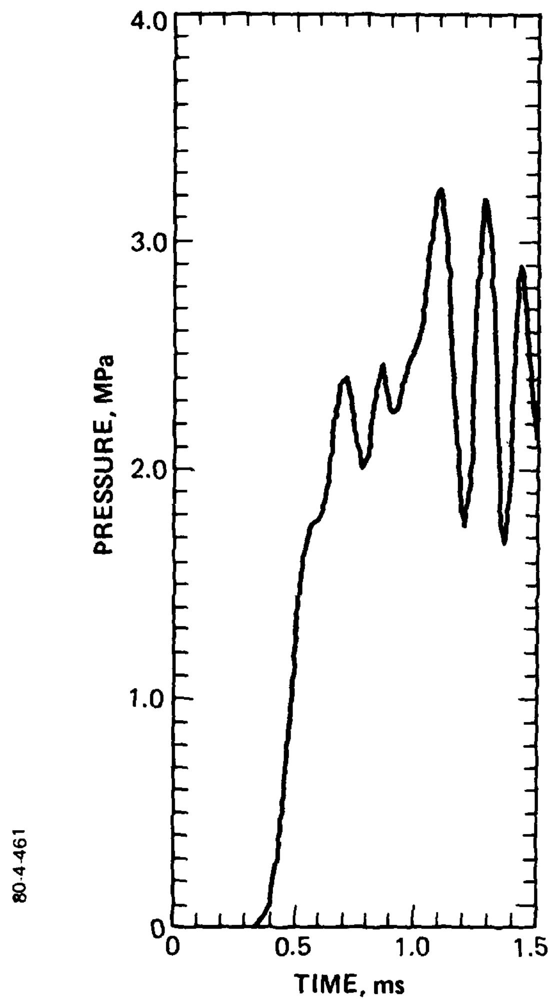

Figure 4.5 Calculated pressure history in water at a range of 0.67 m (2 ft) from the center of a single 1.8 m (6 ft) long PAI propellant tube.

SECTION 5

CONSIDERATION OF HIGH EXPLOSIVE SOURCES FROM A THEORETICAL VIEWPOINT

A two- to three-year investigation of high explosive sources has been conducted by UERD in Shock Block Program. Various explosive charge designs are discussed in References 1 and 2. The charge designs are square, with maximum dimensions of 7.3 m x 7.3 m x 7.6-10.2 cm (24 ft x 24 ft x 3-5 in.). Support for the charge is supplied by a steel plate, and a planar charge is simulated by closely spaced Primacord strands fastened to the plate. Low density foam has been placed near the charge to provide an expansion cavity. Total charge weights have ranged from a few kilograms to almost the 68 kg (150 lb) weight limit in the turning basin of the Norfolk Naval Shipyard.

An additional effort was made to see whether these high explosive designs could be improved. The effort was prompted by recognizing that the addition of a foam cavity around the Primacord array made a substantial improvement in the shape of the waveform. The pulse had an acceptable risetime and maximum pressure level, and did not contain the high pressure spikes that appeared in data obtained from most other designs. These designs incorporating a foam cavity failed in that the pulse duration was too short (Reference 2).

At least three physical processes that could cause the pressure pulse to attenuate rapidly can be identified. These are enumerated on the following page:

1. Excessive motion of the water close to the charge array, caused by the high initial shock pressure. The pressure near the charge is attenuated rapidly by volume expansion.

2. Edge effects due to the finite size of the charge arrays. Expansion of the cavity in the direction parallel to the charge array may be enhanced by rarefaction effects, causing the pressure near the source to drop rapidly.

3. Instabilities in the pressure field in front of the charge array caused by the discrete explosive source and its finite detonation time.

To a very high degree, the pressure history near the source region is directly transmitted to the water, delayed by the transit time through the water. One can easily solve for the velocity at which a "piston" must travel to produce a constant pressure, P, of 20 MPa in the water in front of it (assuming planar symmetry and no divergence effects). Using the relationship

$$P = \rho_o \, cu, \tag{5.1}$$

where for water $\rho_o = 1\ g/cm^3$ and c, the sound speed, is 1.5 m/ms, the piston velocity, u, is calculated to be 13.3 m/s. The fast risetime, however, requires that the piston begin moving instantaneously; thus a shock wave will develop. A 1D calculation was performed to investigate an idealized case corresponding to one of the Shock Block tests (UERD Test 8987), using approximately 32 kg (70 lb) of 42.5 g/m (200 grain/ft) Primacord backed by a steel plate and tamped with 63.5 mm (2.5 in.) of 0.032 g/cm^3 ($216/ft^3$) foam. The total design had dimensions of 6.1 m x 6.1 m x 76.2 mm (20 ft x 20 ft x 3 in.). In the calculation the energy released by the Primacord was spread out evenly over the explosive and foam mass, resulting in a slab source region with an initial density of 0.113 g/cm^3 and pressure of 21.6 MPa (3175 psi). The equation of state for the foam was obtained from Reference 8. This 1D slab source was then allowed to drive water in the calculation; the steel plate was considered a rigid boundary. The pressure history in the water is shown in Figure 5.1. An initial shock is seen, followed by a slow pressure decay. At 2.5 ms the pressure is still 15 MPa (2200 psi). The velocity at the source-water interface is found to decay from 13.9 m/s at 20 μs to 8.9 m/s at 2.5 ms. These values agree well with the interface ("piston") velocity calculated by Equation 5.1.

This initial 1D calculation showed that there was enough energy in the Primacord charge to almost deliver the desired waveform in the water. However, the calculated pressure pulse had a duration which was much longer than obtained in the experiment. The physical processes discussed above must be responsible for the marked departure of the measured waveforms (Reference 2) from the idealized waveform.

A series of calculations was then performed to assess the impact of the physical effects. In all calculations the Primacord was assumed to be a continuous sheet with an areal energy density approximately equal to a 32 kg (70 lb) Primacord strand charge.* The thickness of the sheet was calculated to be 0.0451 cm; its areal density, 0.08 g/cm^2 (0.52 $g/in.^2$). In the first calculation, the charge was allowed to expand directly into water, and the steel plate was assumed to be a rigid boundary. Figure 5.2 shows the pressure history in the water from this calculation. The initial pressure is very high, over 100 MPa

*This results in a strand spacing of 5.1 cm (2 in.) across a 6.1 m x 6.1 m (20 ft x 20 ft) steel plate.

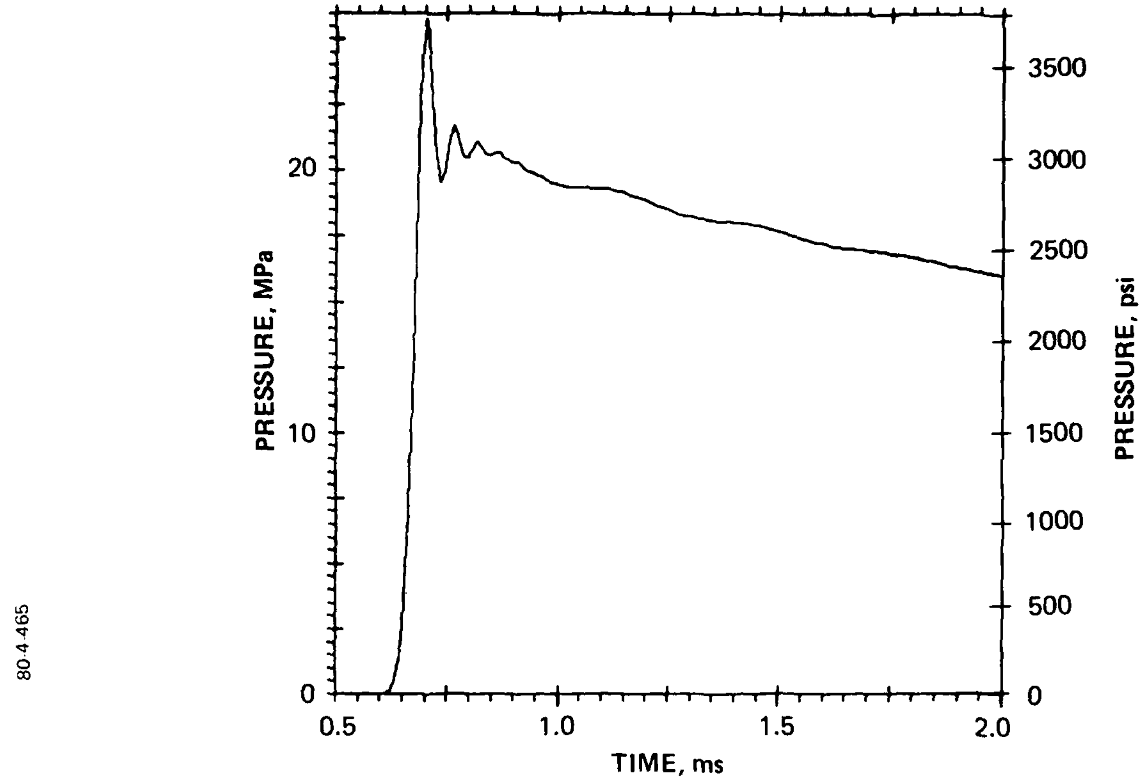

Figure 5.1 Calculated pressure history in water 1.07 m (3.5 ft) in front of an HE-foam slab charge 6.35 cm (2.5 in.) thick where the HE energy is initially spread out uniformly over the foam. (The areal energy density is equivalent to a 31.8 kg [70 lb] Primacord charge affixed to a 6.1 m x 6.1 m [20 ft x 20 ft] steel plate).

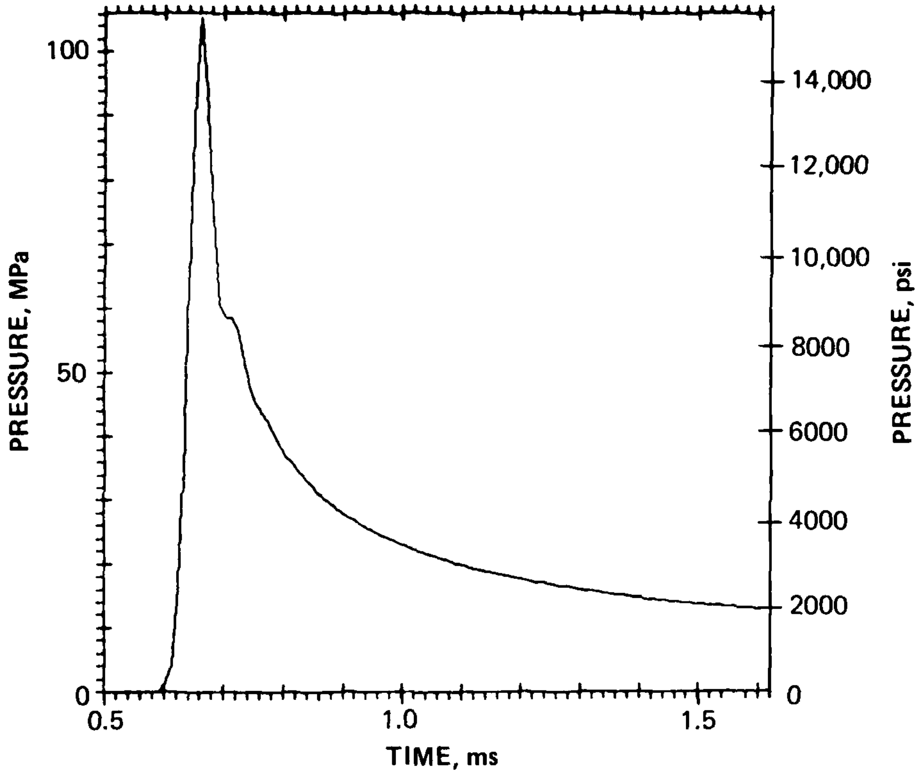

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Figure 5.2 Calculated pressure history in water 1.07 m (3.5 ft) in front of a HE slab charge with an areal energy density equivalent to a 31.8 kg (70 lb) Primacord charge affixed to a 6.1 m x 6.1 m (20 ft x 20 ft) steel plate (no expansion cavity).

(14.7 kpsi); the attenuation, very rapid. In the second calculation, (Figure 5.3) a 6.35 cm (2.5 in.) foam (Reference 8) expansion cavity was placed between the explosive sheet and the water. The pressure history from that calculation shows that the initial maximum pressure is reduced to 60 MPa (8,820 psi), and that the pressure is relatively constant at times beyond 1 ms at a level of 12 MPa (1760 psi). The later-time oscillations in the pressure amplitude are due to shock reverberation within the HE/foam cavity. The results of these two calculations indicated that a greater degree of decoupling of the initial HE shock from the water was required. The late-time pressures were not seriously overestimated due to the assumption that the steel backing plate acted as a rigid wall. Allowing the steel plate to expand in another calculation lowered the late-time pressure by 10 percent, but still did not allow the pressure to drop to zero, as the experimental data indicate. This observation indicates that charge edge effects and/or interface instabilities, including cavitation, might be very important in reducing the late-time pressure. The initial high pressure spike is also not seen in the data, but the appropriate pressure gage on Shot 8987 was set for a maximum pressure of 25 MPa. Thus it was probably unable to record this high frequency pressure pulse.

Data from another test (UERD Test 9031) were also analyzed. This test contained twice the areal charge density, but the primacord charge was sandwiched between two 6.35 cm (2.5 in.) foam sheets, and backed on one side by a steel plate. These data can be compared with the calculational results of Figure 5.3 because the charge is symmetric, neglecting the steel plate. The comparison of the calculated with the experimental results is shown in Figure 5.4. The pressure gage set ranges were higher, and the high pressure spike predicted by the calculation was as

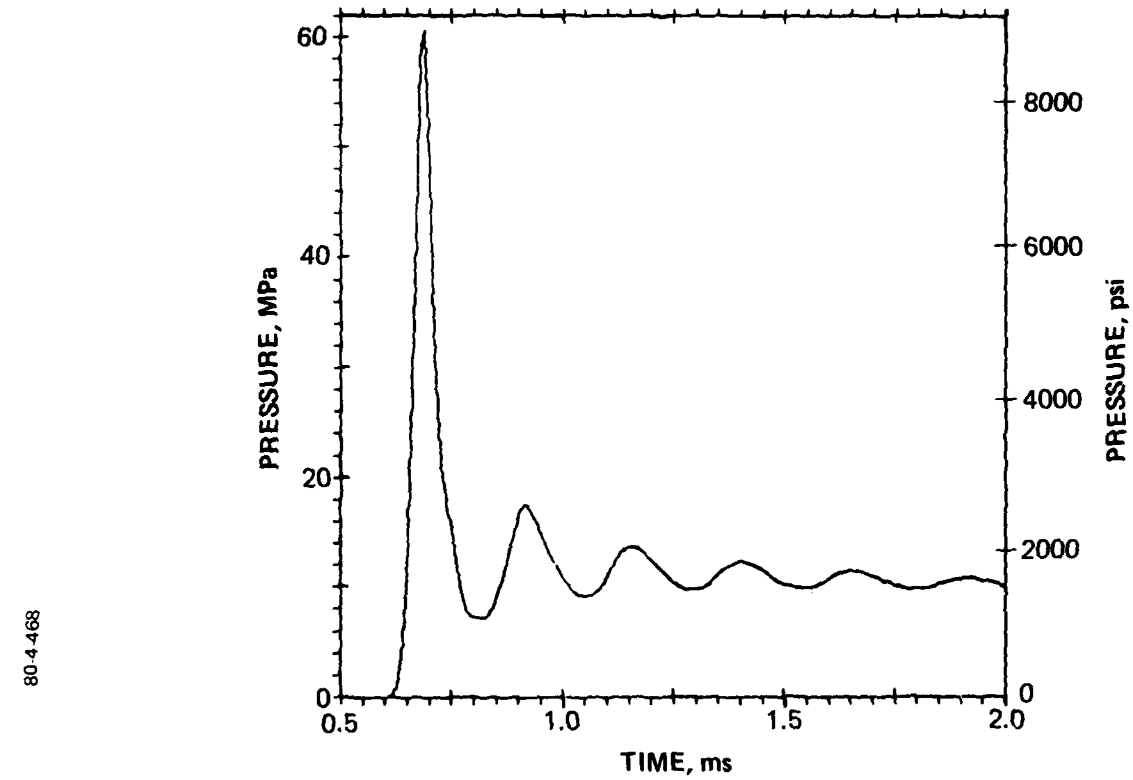

Figure 5.3 Calculated pressure history in water 1.07 m (3.5 ft) in front of a HE sheet charge separated from the water by a 6.35 cm (2.5 in.) thick foam-filled expansion cavity (0.032 g/cm^3, 2 lb/ft^3).

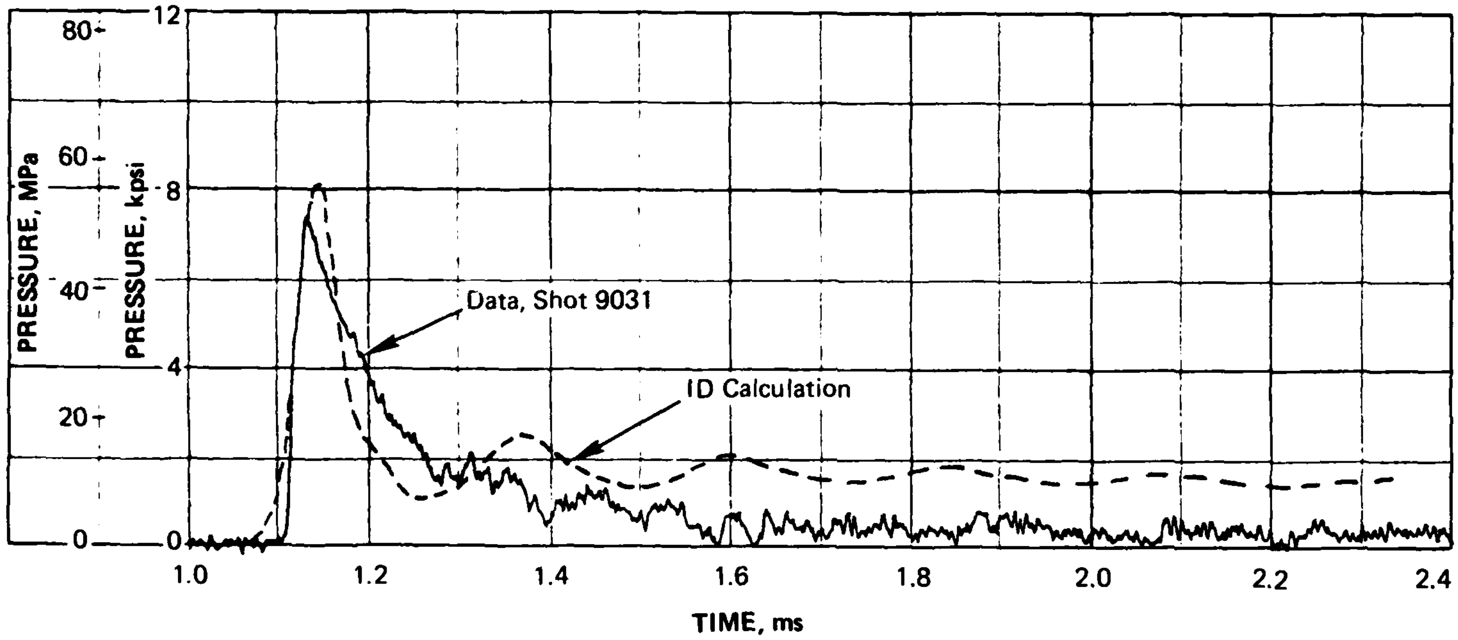

Figure 5.4 Comparison of calculated and measured pressure history 1.22 m (4 ft) in front of slab charge for UERD Shot 9031, pressure gage P1 (experiment data used with the permission of Mr. J.D. Gordon, UERD).

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observed. Some evidence of shock reverberation within the HE/ foam cavity is also seen in the data, but the measured late-time pressure generally drops faster than that calculated.

The above comparison shows that the initial shock could be calculated reasonably well for only 0.2 ms from the time of maximum pressure. This comparison indicates that for times after the initial pulse, the source region cannot be treated in 1D. Charge edge effects and interface instabilities probably contribute heavily to pressure damping in the source region at later times. To achieve a pressure pulse with a 5 ms duration, they must be minimized.

A few additional calculations were performed to see whether an improved HE design could be generated. It was assumed that the source region should be enclosed by steel (to eliminate edge effects), that the charge should be adequately decoupled from the water (to minimize the initial shock), and that the explosive gases should drive a steel plate (to minimize interface instabilities). Since such a charge structure is initially enclosed, it is possible to enhance the charge decoupling further by using an air-filled rather than a foam-filled cavity. An initial design is shown in Figure 5.5. Since the structure is basically symmetric about the plane of the charge, it was necessary to calculate only half the problem. Figure 5.6 shows the result of a planar 1D calculation, which decoupled the HE with a 3 cm (1.2 in.) air (variable specific heat ratio EOS) gap and included a 1.27 cm (0.5 in.) steel plate between the air and the water. This pulse compares favorably with the ideal pulse shown in Figure 5.1, but the pressure attenuation with time is slightly greater.

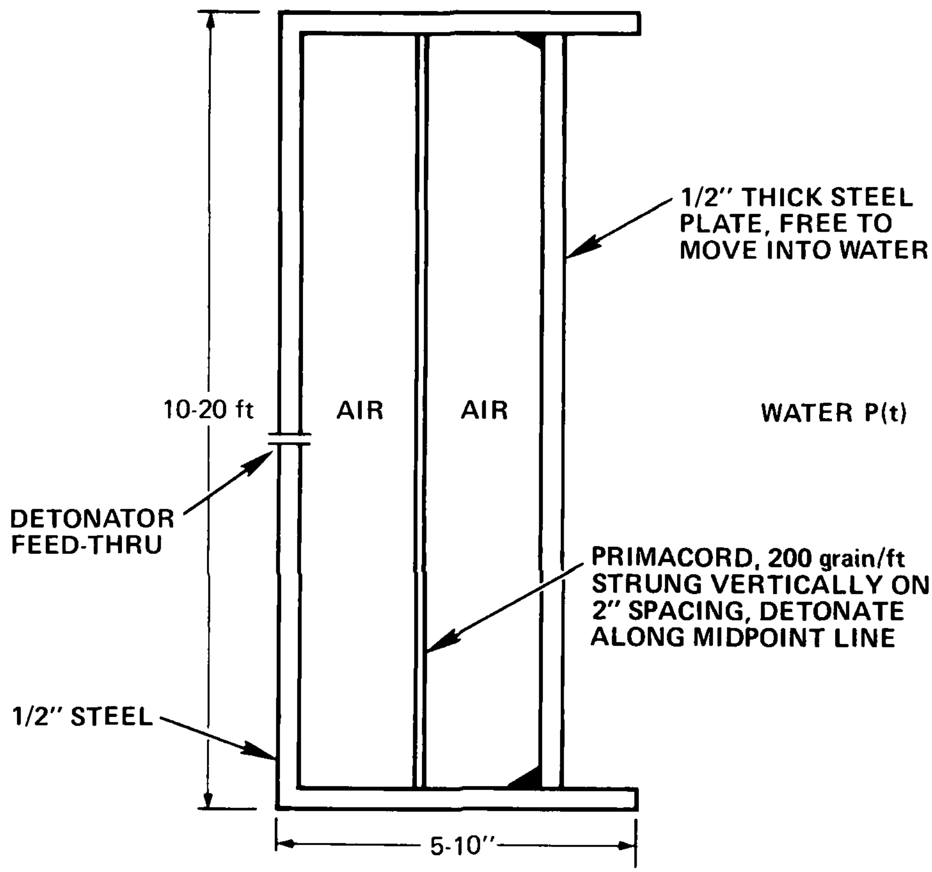

Figure 5.5 Shock Block initial design for improved HE driver system.

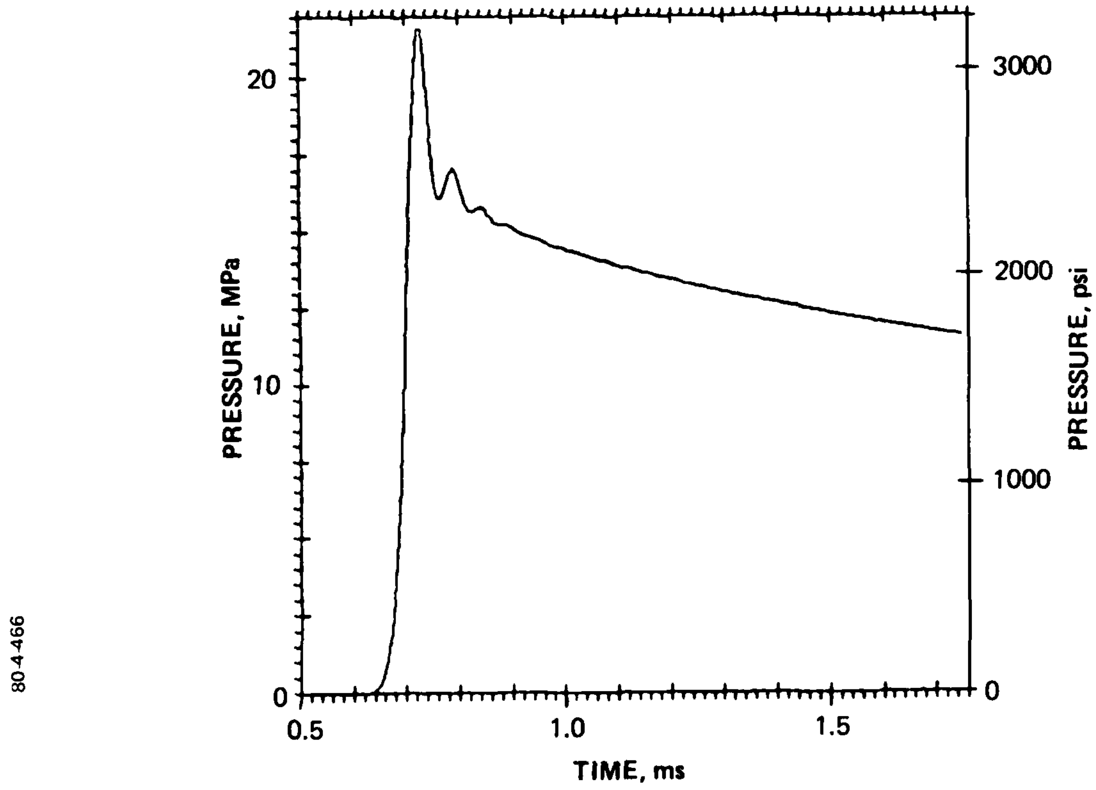

Figure 5.6 Calculated pressure history in water 1.07 m (3.5 ft) in front of a HE slab charge decoupled from the water by a 3 cm (1.2 in.) air gap and a 1.27 cm (0.5 in.) steel plate (charge design as shown in Figure 5.5).

The results of this effort indicate that a planar HE system which will produce a fast risetime and a long duration pulse in water is theoretically feasible. The amplitude of the pulse will vary with time, due to the inevitable expansion of the source cavity, so that an additional pressure source might be needed to maintain a constant-amplitude pulse.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

Physics International Company (PI) participated in a DNA-sponsored Nuclear Weapon Effect (NWE) simulation program. The purpose of the program, called the Shock Block Program, is to generate a planar pressure pulse in water. The pulse is characterized by a short risetime (~ 0.1 ms) and a long pulse width ($\gtrsim$ 5 ms) at an amplitude of approximately 20 MPa. The Underwater Explosions Research Division (UERD) of the David W. Taylor Naval Ship Research and Development Center, Portsmouth, Virginia, has major responsibility for testing various models with a pressure pulse of the above type in a water environment.

PI had responsibility for investigating the feasibility of using propellants, or HE and propellants, to produce the desired underwater waveform. This responsibility included literature surveys, finite-difference calculations, and small-scale testing, but no full-scale testing of planar charge arrays of the size required for model testing [approximately 6.1 m x 6.1 m (20 ft x 20 ft) or greater].

Early in the investigation it became clear that unconfined conventional propellants alone would not produce the desired risetime. An unconventional propellant was seriously considered because calculations performed using its properties indicated that it could produce the desired risetime; it was dropped because of its excessive cost.

Calculations indicated that HE/propellant systems could deliver the desired pulse, if the initial HE shock was ignored. Small-scale experiments with such sources revealed the propellant did not produce a predictable absolute risetime (the time from propellant initiation to significant gas generation was variable), and also did not perform well when subjected to the HE shock.

A confined propellant system utilizing a series of aluminum tubes containing a powdered propellant designed by Physics Applications, Inc. (PAI), was evaluated calculationally. The results of that effort are in essential agreement with the UERD interpretation of test results: the confined propellant system generated a pressure pulse with an acceptable risetime and a long duration (~ 3 ms) at an average amplitude of about a factor of four less than desired, but the pulse in the water was not planar due to the slow burn velocity of the propellant along each individual tube. The calculations showed that the planarity of this system could be improved by igniting the propellant in a greater number of places, and that excessive pressure spikes due to nonuniform tube rupturing might be smoothed by providing a foam expansion cavity.

Finally, a theoretical examination of HE designs tested in the past by UERD indicated that the pulse duration is dominated by shock wave effects, rarefactions from the charge edge, and interface instabilities, possibly including cavitation. Further calculations showed that the pulse shape could be significantly improved by using an air-filled expansion cavity. It is strongly suggested that another experimental series be performed at UERD during the next fiscal year using HE systems, and/or HE/PAI propellant systems. The design tested should have the following general properties:

1. The explosive and/or propellant source should be decoupled from the water by an air or low-density foam cavity.

2. A steel sleeve should be welded around the charge edge to minimize rarefactions.

3. The driver gas should be separated from the water by a steel plate to prevent instabilities from developing.

Furthermore, any such experimental effort should be preceded by 1D and possibly 2D prediction calculations.

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